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AUGUST 1977

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LORAN-D Prototype Tethered Antenna Impedance and Radiation Measurements,

J.L. HECKSCHER
R.W. WHIDDEN

Technical rept.,

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ROME AIR DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
GRIFFISS AIR FORCE BASE, NEW YORK 13441

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This technical report has been reviewed and approved for publication.

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Allan C. Schell

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Electromagnetic Sciences Division

FOR THE COMMANDER

John P. Huss

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On 23 March 1977, personnel from the Rome Air Development Center (RADC) and the Electronics System Division (ESD) experimentally determined the input impedance and radiation parameters of a prototype balloon-supported, 500-ft toploaded LORAN transmitting antenna at Holloman AFB, New Mexico The tests were conducted to verify theoretical calculations and to provide data for use in designing matching networks.

The input impedance was measured at seven frequencies: 82.3, 91.2, 94.5, 95.1, 100.1, 104.5, and 112.9 kHz, using a bridge substition method.

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Radiation parameters were estimated at a single frequency, 99.3 kHz. Values for the effective antenna capacitance, inductance, and total resistance, as well as for the radiation resistance and effective height, are reported and discussed.

Preface

We are grateful to Dr. E. A. Lewis for valuable discussions regarding measurement techniques, and we thank Capt. R. V. Gressang (ESD/DCLG) for assistance with the field measurements.

This work was funded in part by the Tactical LORAN System Project Office.

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Contents

Illustrations

Tables

LORAN-D Prototype Tethered Antenna Impedance and Radiation Measurements

1. INTRODUCTION

A prototype balloon-supported LF transmitting antenna, designed for emergency use with the LORAN-D tactical navigation system, was deployed at Holloman AFB, New Mexico, on 23 March 1977, in an operational test of antenna properties and of the integrity of antenna system parts. Personnel from the Rome Air Development Center (RADC/ET) and the Electronic Systems Division (ESD/DC) measured some of the antenna electrical parameters, including input impedance, radiation resistance, and effective height.

The antenna consisted of a single 500-ft, top-loaded vertical element supported over a ground plane by a barrage-type balloon. Three 792-ft guy cables, anchored 120° apart on the ground, held the vertical wire stationary. The top 700 ft of each cable was electrically conducting, to serve as a top-load. The ground plane consisted of 6 radial wires, each 150-ft long, attached to copper ground rods driven into the desert soil. A diagram of the antenna configuration is shown in Figure 1.

(Received for publication 15 August 1977)

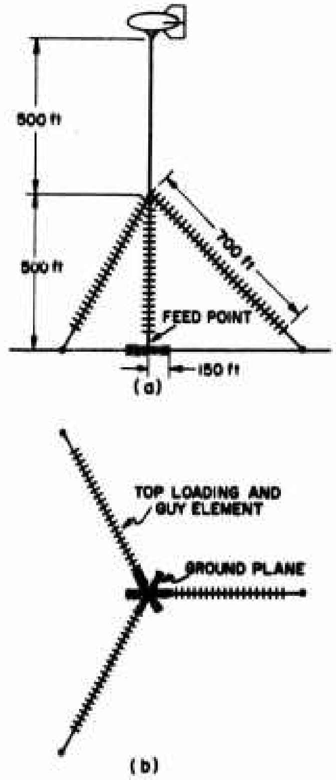

Figure 1. Profile View of Tethered Antenna (a) and Plan View (b). Active portions shown with cross lines

2. MEASUREMENT CONCEPTS

2.1 Antenna Input Impedance

An equivalent circuit for the low frequency antenna is shown in Figure 2. The antenna is electrically short, so the reactance presented at terminals A-B is capacitive. Therefore we can write

$$-\frac{1}{\omega_1 C_1} = -\frac{1}{\omega_1 C_A} + \omega_1 L_A , \tag{1}$$

where C_1 is the "effective" or apparent capacity at terminals A-B at frequency ω_1. For frequency ω_2 we have

$$-\frac{1}{\omega_2 C_2} = -\frac{1}{\omega_2 C_A} + \omega_2 L_A . \tag{2}$$

Combining Eqs. (1) and (2), we can solve for the unknowns, L_A and C_A, in terms of the measureable quantities C_1 and C_2:

$$L_A = \frac{\frac{1}{C_1} - \frac{1}{C_2}}{\omega_2^2 - \omega_1^2} , \tag{3}$$

$$\frac{1}{C_A} = \frac{\frac{\omega_2^2}{C_1} - \frac{\omega_1^2}{C_2}}{\omega_2^2 - \omega_1^2} . \tag{4}$$

Thus by measuring the capacitive reactance at A-B at two different frequencies, the equivalent circuit capacity and inductance can be determined.

The equivalent series resistance, R_A, can be measured if a series inductor L_s (having a small series resistance r_s) is used to cancel the capacitive reactance at A-B. Thus in Figure 3, if

$$-\omega L_s = -\frac{1}{\omega C_A} + \omega L_A , \tag{5}$$

then

$$Z_{A'B'} = R_A + r_s , \tag{6}$$

from which R_A may be found if r_s is known.

Figure 2. Antenna Equivalent Circuit

C_A = ANTENNA CAPACITY, L_A = ANTENNA INDUCTANCE,
R_r = RADIATION RESISTANCE, R_g = GROUND RESISTANCE,
R_{CU} = CONDUCTOR RESISTANCE, R_{SD} = SERIES DIELECTRIC RESISTANCE.

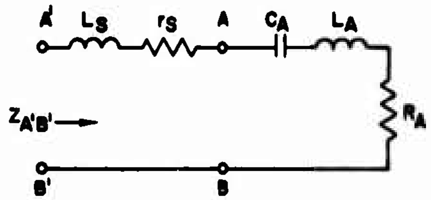

Figure 3. Use of Series Inductance to Resonate Antenna Effective Capacity

L_S = SERIES INDUCTANCE, r_S = SERIES RESISTANCE.

2.2 Radiation Parameters

The radiation resistance, R_r, of a transmitting antenna can be defined in terms of the radiatedpower, W_r, and corresponding antenna base current, I,

$$R_r = \frac{2\,W_r}{I^2}\,.$$

Assuming an infinitesimal dipole, W_r can be determined from a field strength measurement at a known distance from the antenna, so the radiation resistance can be expressed as

$$R_r = \frac{1}{90}\left(\frac{E_V \cdot r}{I}\right)^2 \qquad (7)$$

where E_V is the field strength, V/m; r is the distance, m; and I is the antenna current, amperes (see Section A1). Eq. (7) assumes the field strength is proportional to the inverse of the distance r from the antenna, which requires measurements to be made in the region $r >> 2\pi/\lambda$ to minimize near-field effects.

The effective height, h_e, of an antenna can be defined as that length of uniform current of amplitude I which radiates the same power as the actual antenna having base current I. Using the same units as in Eq. (7), the effective height is

$$h_e = \frac{796\, E_V \cdot r}{f \cdot I} \qquad (8)$$

where f is the frequency in kHz (see Section A2).

3. MEASUREMENTS AND DISCUSSIONS

3.1 Antenna Impedance Measurements

The antenna input reactance and resistance were measured by a substitution method in conjunction with a resonance bridge.[1] The bridge circuit, along with the oscillator and amplifier used to energize it is shown in Figure 4. The bridge null was sensed with a two-channel oscilloscope set on the subtract mode; frequency was read from a counter display.

On the basis of pre-calculated antenna parameters, several coils were wound so as to resonate the antenna at various frequencies nominally between 90 and 110 kHz. Two precision decade capacitor boxes, calibrated by PMEL, were used as the measurement standard; along with individual 5 percent silver mica capacitors, values up to 11,110 pf could be synthesized to within about 10 pf.

1. ITT, Reference Data for Radio Engineers (5th Ed.) (1972) H. W. Sams & Co. Inc., Indianapolis, Indiana, p 11-3.

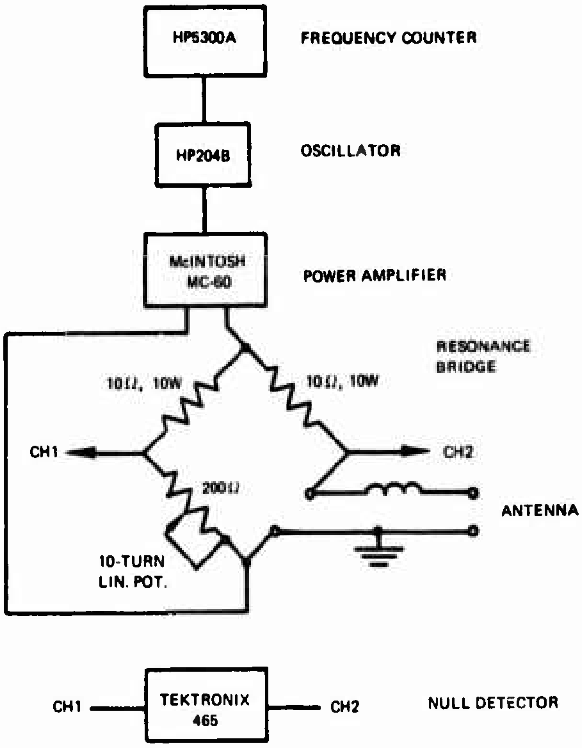

Figure 4. Setup for Antenna Impedance Measurements

The actual measurements were performed in two stages. First, a coil was connected in series between the antenna and the bridge, and the frequency and potentiometer setting were varied for best null indication on the oscilloscope. The frequency and potentiometer setting were recorded. Second, the precision capacitor boxes were substituted for the antenna, and the capacity and potentiometer varied until the best null was again obtained. The total precision capacity was then recorded. This completed the measurement sequence at the recorded frequency. Data for seven such tests are given in Table 1.

Table 1. Recorded Data – Antenna Impedance Measurements

Test	Frequency (kHz)	Capacity (pF)	Potentiometer Setting
1	82.3	6081	1.76
2	91.2	6881	1.74
3	94.5	7262	1.79
4	95.1	7340	1.81
5	100.1	7986	1.78
6	104.5	8880	1.75
7	112.9	11,081	1.94

Six estimates of antenna capacity and inductance, calculated by Eqs. (3) and (4) using data at adjacent frequencies, are shown in Table 2.

Table 2. Calculated Antenna Parameters

Test Pairs	C_A (pF)	L_A (μH)
1-2	4024	314.4
2-3	4020	315.1
3-4	4045	310.8
4-5	4205	284.4
5-6	3767	354.3
6-7	4045	311.9

It is evident that the two calculations involving Test 5 differ significantly from the other four results. Test 5 was conducted at 100.1 kHz; it is possible that strong signals at 100.0 kHz from the 1 MW Loran transmitter at Searchlight, NV (870 km distant) interfered with the measurement. If the two Test 5 computations are considered invalid, and the four remaining results are averaged, we obtain

$$C_A = 4033 \pm 13 \text{ pF} ,$$

$$L_A = 313.1 \pm 2.0 \ \mu\text{H} .$$

The total antenna plus coil resistance was determined from the dial setting assuming a linear 20 ohms per turn potentiometer. The average of Tests 1 through 7 (excluding No. 5) is 1.80 ± 0.03, corresponding to 36.0 ± 0.6 Ω. The coil resistance was a small fraction of this total, at most 1.0 Ω, so that about 35 Ω can be attributed to the antenna. Such a large value would be excessive in an actual transmitting system; however, there was no requirement that the antenna be efficient for these preliminary tests. Had a more extensive ground plane been constructed, the effective antenna resistance would no doubt have been much lower.

3.2 Antenna Radiation Measurements

Due to the short time available, field strength measurements were conducted only at one site. The antenna was energized through a series inductance, with the frequency adjusted to produce a maximum current. A Pearson current probe, Model 410, sensed the antenna current I (see Figure 5). The field was measured with a Singer Radio Interference - Field Intensity Measuring Equipment, Model NM - 12AT, using a collapsible, shielded loop antenna. Table 3 shows the frequency, current, NM - 12AT meter reading, attenuator setting, and appropriate "antenna correction factor" (from a calibration chart supplied with the instrument) recorded during the test.

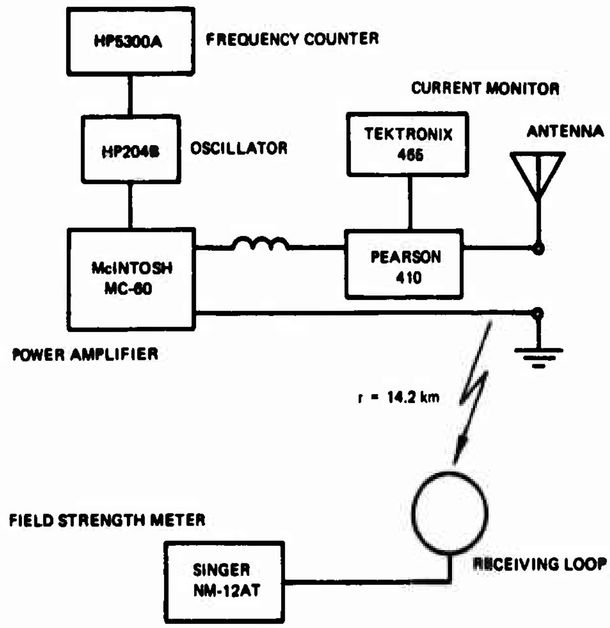

Figure 5. Setup for Antenna Radiation Measurements

Table 3. Antenna Radiation Parameter Data

f(kHz)	I (A, p-p)	NM-2AT Readings		
		Meter (dB)	Atten. (dB)	Ant. Corr (dB)
99.3	2.4	28	−20	48.5

The sum of the meter, attenuator, and antenna correction readings gives a field strength of 56.5 dB above one μV/m, rms (to within ± 2 dB, see NM-12AT Instruction Manual). Then the field amplitude is

$$|E_V| = 945\ \mu V/m \pm 26\%\ .$$

The antenna current amplitude is half the peak-to-peak value

$$I = 1.2\ A\ .$$

Distance from the transmitting antenna to the receiving site was scaled from the Holloman, NM 15-min quadrangle map, U.S. Geological Survey (1948). Exact transmitting antenna coordinates were unavailable, however, the Scat Site coordinates (32° 55' 43"N, 106° 04' 18"W) were very near the "4181" bench mark on the map. The receiving site was near the Frequency Monitoring Station ("Freak"), 150 feet NE of a marker labelled 32° 48' 59"N, 106° 08' 40"W. On the quadrangle map, this location almost exactly coincided with the "4091" bench mark. The distance between the two bench marks was taken as a suitable value for r,

$$r = 14.2 \text{ km} .$$

Substituting the above values into Eqs. (7) and (8), we find

$$R_r = 1.38\ \Omega \pm 52\% ,$$

$$h_e = 89.4 \text{ m} \pm 26\% .$$

Since the results are based on observations at only one site, they should not be regarded with high confidence. The possibility of local anomalies in field strength, such as might be caused by fences, buried cables, or abrupt discontinuities in terrain conductivity was not investigated, nor was any attempt made to determine the effect (if any) of the antenna near fields. The results are, however, in reasonable agreement with theoretical estimates of Drane.[2]

2. Drane, C.J. (Private Communication).

Appendix A

Radiation Resistance and Antenna Effective Height

A1. Radiation Resistance

The far fields of an infinitesimal vertical dipole of current amplitude I, length h/2, located just above a perfectly conducting plane are[3]

$$E_\theta = \frac{j\omega\mu I h}{4\pi r} \sin\theta \, e^{-jkr}, \tag{A1}$$

$$H_\varphi = \frac{jkIh}{4\pi r} \sin\theta \, e^{-jkr} = E_\theta / Z_o, \tag{A2}$$

$$Z_o = \sqrt{\mu/\epsilon} \simeq 120\,\pi,$$

for $0 \le \theta \le \frac{\pi}{2}$, and are zero elsewhere. At a distant point just above the surface

$$|E_{\theta \to \pi/2}| \equiv |E_V| = \frac{\omega\mu I h}{4\pi r}, \tag{A3}$$

and therefore

3. Ramo, S., Whinnery, J.R., and Van Duzer, T. (1965) Fields and Waves in Communication Electronics, John Wiley & Sons, Inc., New York, pp 642-651.

$$|E_\theta| = |E_V| \sin\theta \,, \tag{A4}$$

$$|H_\varphi| = \frac{|E_V|}{Z_o} \sin\theta \,. \tag{A5}$$

The time-average Poynting vector is radial, and equal to one-half the product of the magnitudes of the electric and magnetic field vectors

$$\overline{P_r} = \frac{|E_V|^2}{2\,Z_o} \sin^2\theta \,. \tag{A6}$$

The total power radiated is the surface integral of $\overline{P_r}$ over a hemisphere of radius r

$$W_r = \int P_r\, dA = \int_0^{\pi/2} \frac{|E_V|^2}{2\,Z_o} \sin^2\theta \cdot 2\pi r^2 \sin\theta\, d\theta$$

$$= \frac{|E_V|^2\, r^2}{180} \;; \tag{A7}$$

Then the radiation resistance is defined by

$$R_r \equiv \frac{2\,W_r}{I^2} = \frac{1}{90} \left(\frac{E_V \cdot r}{I}\right)^2 \,. \tag{A8}$$

A2. Antenna Effective Height

By Eq. (A3) an antenna of effective height h/2 produces a field

$$|E_V| = \frac{\omega \mu I}{2\pi\, r} \left(\frac{h}{2}\right).$$

Therefore

$$h_e = \frac{h}{2} = \frac{1}{f\mu} \left(\frac{E_V \cdot r}{I}\right)$$

$$= \frac{796}{f_{kHz}} \left(\frac{E_V \cdot r}{I}\right) \,. \tag{A9}$$

METRIC SYSTEM

BASE UNITS:

Quantity	Unit	SI Symbol	Formula
length	metre	m	...
mass	kilogram	kg	...
time	second	s	...
electric current	ampere	A	...
thermodynamic temperature	kelvin	K	...
amount of substance	mole	mol	...
luminous intensity	candela	cd	...

SUPPLEMENTARY UNITS:

Quantity	Unit	SI Symbol	Formula
plane angle	radian	rad	...
solid angle	steradian	sr	...

DERIVED UNITS:

Quantity	Unit	SI Symbol	Formula
Acceleration	metre per second squared	...	m/s^2
activity (of a radioactive source)	disintegration per second	...	(disintegration)/s
angular acceleration	radian per second squared	...	rad/s^2
angular velocity	radian per second	...	rad/s
area	square metre	...	m^2
density	kilogram per cubic metre	...	kg/m^3
electric capacitance	farad	F	A·s/V
electrical conductance	siemens	S	A/V
electric field strength	volt per metre	...	V/m
electric inductance	henry	H	V·s/A
electric potential difference	volt	V	W/A
electric resistance	ohm		V/A
electromotive force	volt	V	W/A
energy	joule	J	N·m
entropy	joule per kelvin	...	J/K
force	newton	N	$kg\cdot m/s^2$
frequency	hertz	Hz	(cycle)/s
illuminance	lux	lx	lm/m^2
luminance	candela per square metre	...	cd/m^2
luminous flux	lumen	lm	cd·sr
magnetic field strength	ampere per metre	...	A/m
magnetic flux	weber	Wb	V·s
magnetic flux density	tesla	T	Wb/m^2
magnetomotive force	ampere	A	...
power	watt	W	J/s
pressure	pascal	Pa	N/m^2
quantity of electricity	coulomb	C	A·s
quantity of heat	joule	J	N·m
radiant intensity	watt per steradian	...	W/sr
specific heat	joule per kilogram-kelvin	...	J/kg·K
stress	pascal	Pa	N/m^2
thermal conductivity	watt per metre-kelvin	...	W/m·K
velocity	metre per second	...	m/s
viscosity, dynamic	pascal-second	...	Pa·s
viscosity, kinematic	square metre per second	...	m^2/s
voltage	volt	V	W/A
volume	cubic metre	...	m^3
wavenumber	reciprocal metre	...	(wave)/m
work	joule	J	N·m

SI PREFIXES:

Multiplication Factors	Prefix	SI Symbol
1 000 000 000 000 = 10^{12}	tera	T
1 000 000 000 = 10^{9}	giga	G
1 000 000 = 10^{6}	mega	M
1 000 = 10^{3}	kilo	k
100 = 10^{2}	hecto*	h
10 = 10^{1}	deka*	da
0.1 = 10^{-1}	deci*	d
0.01 = 10^{-2}	centi*	c
0.001 = 10^{-3}	milli	m
0.000 001 = 10^{-6}	micro	μ
0.000 000 001 = 10^{-9}	nano	n
0.000 000 000 001 = 10^{-12}	pico	p
0.000 000 000 000 001 = 10^{-15}	femto	f
0.000 000 000 000 000 001 = 10^{-18}	atto	a

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